Understanding Glider Performance

This is a quick look at what your sailplane can and cannot do—and why. It isn't intended to teach you how to design your own glider, nor (God forbid!) to modify an existing ship. It is meant simply to provide you with a better understanding of your aircraft and why it was designed the way it was designed.

Unavoidably, there's a little bit of math involved, but nothing exotic. The design of any aircraft, even of a purely recreational sailplane, involves many engineering compromises and tradeoffs; and even the most math-adverse among us has to choose an airspeed to use between climbs, a bank angle to use in thermals, etc—in other words, has to choose *numbers*. After all, the question of where to set your MacCready ring isn't answered very well by the information that "Dude, the lift today is pretty gnarly!"

For our purposes, we'll consider an imaginary sailplane that's a sort of composite of the existing fleet. Let's say that this ficticious glider has a wingspan of 15 meters, weighs 800 pounds ready for tow and has a best glide ratio of 40:1 at a speed of 50 KIAS. As you will see, just these few figures will pretty well define the entire performance capability of this imaginary glider...for example, we can figure that at 100 KIAS the L/D will be just about 20:1. More on that, later.

Lift

A basic requirement for any aircraft is that the design must somehow provide for the creation of sufficient lift to support flight. This isn't difficult, however, the real issue is providing enough lift at whatever stall speed is desired. The FARs require that any fixed-wing civil aircraft with less than two engines must have a stall speed less than 61 kts, but for gliders a more stringent requirement is that we have to be able to profitably circle inside thermals. This usually puts the 1-g stall speed at about 32 KIAS or so.

Most of the airfoils that could reasonably be chosen for a 15-meter sailplane have pretty much the same high-lift characteristics, so airfoil selection doesn't play much of a role in deciding on wing area. In the section on drag, to follow shortly, we will see that a high aspect ratio (the ratio between the wing's span and its average chord) is desirable, but at the same time the designer has to compromise between aspect ratio and wing area. The choice boils down like this:

$$\textbf{(aspect ratio) x (wing area) = (wingspan)}^2$$

So, obviously, because the wingspan is already chosen (15 meters, by the class rules) for the designer, there is an upper limit to aspect ratio.

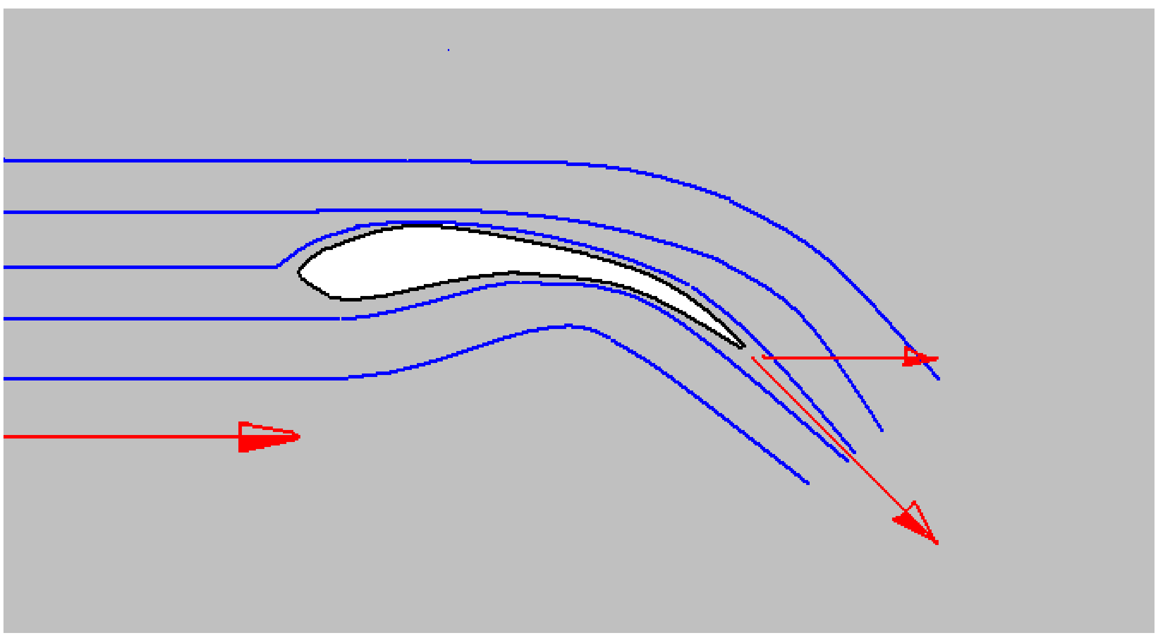
There's another consideration: a high aspect ratio is aerodynamically efficient, but structurally inefficient. A wing acts as a beam—that is, it carries its load in

bending. It is more difficult to design a long, narrow wing than a short, wide one—and further, a narrow wing is also going to be a thin wing! Spar depth is a major consideration: the strength of a beam is proportional to the cube of the depth, so that cutting a wing's thickness in half without changing anything else makes it only one-eighth as strong...from this, you can easily see why the introduction of carbon fiber made such a difference to sailplane designers.

In the late 1950s NASA attemoted to design a sailplane for ultrahigh altitude (60,000+ ft) research in waves. With the materials available at the time, it was impossible to design a wing thin enough to avoid supersonic airflow—and so the project was shelved.

Drag

Sailplane drag falls into two broad categories: induced drag and profile drag. Induced drag is a result of the generation of lift, while profile drag is a catch-all term that includes drag due to frontal area, interference between wing, fuselage and tail feathers—and skin friction, which on a sailplane is the major source of profile drag. We'll consider induced drag first.



Imagine this airfoil stationary, with the air flowing from left to right. Suppose that there is absolutely no skin friction whatsoever—and that the air flows off the trailing edge with the same speed as that with which it arrives from the left. In order to create lift, the airfoil has to push the air downward; air has mass, and so 'pushes back'—and it is this reaction we experience as lift. Notice, however, that in turning the air downward, the airfoil has reduced the horizontal component of the air's velocity (as indicated by the shorter horizontal arrow at the trailing edge.)

Again, the air has mass, and so pushes back—and this is the reaction we know as induced drag.

Induced drag is an unavoidable byproduct of the creation of lift.

To minimize induced drag, we have to minimize the angle through which we redirect the air flowing past the airfoil. How to do this? By handling more air: instead of turning a small amount of air through a great angle, we can turn a larger mass of air through a smaller angle...there are two ways to do this. We can use a short wingspan and fly very fast (this is what jet fighters do), or we can fly slowly provided we use a large wingspan. More precisely, we can use a wing with a large span for its area: a high aspect ratio**.**

Doubling the aspect ratio cuts induced drag in half.

And this is why sailplanes have long, narrow wings.

Incidentally, for minimum induced drag, the ideal spanwise lift distribution should be elliptical—this was the rationale behind the famous elliptical planform of the Supermarine Spitfire, for example. However, to accurately construct an elliptical wing it is necessary to overcome enormously complicated difficulties, and so designers generally adopt the slight compromise of tapered, double-tapered or even triple-tapered wings. In addition to pratically minimizing induced drag, this strategy also provides for a lighter structure and better roll response.

When we fly a sailplane at high speed, as far as induced drag goes we are really winning the game: doubling the indicated airspeed cuts the induced drag, already low, to a quarter of its previous value. So, we can easily see, high aspect ratio most benefits us at low speeds or when we are operating at high angles of attack —such as when thermaling.

How much drag are we talking about?

At the indicated airspeed for best L/D, induced drag and profile drag are exactly equal. Do you remember our imaginary, fleet-composite sailplane? It was assumed to have a best L/D = 40 and to weigh 800 pounds at takeoff. At best L/D, knowing that Lift= Weight (almost), we can calculate the total drag as

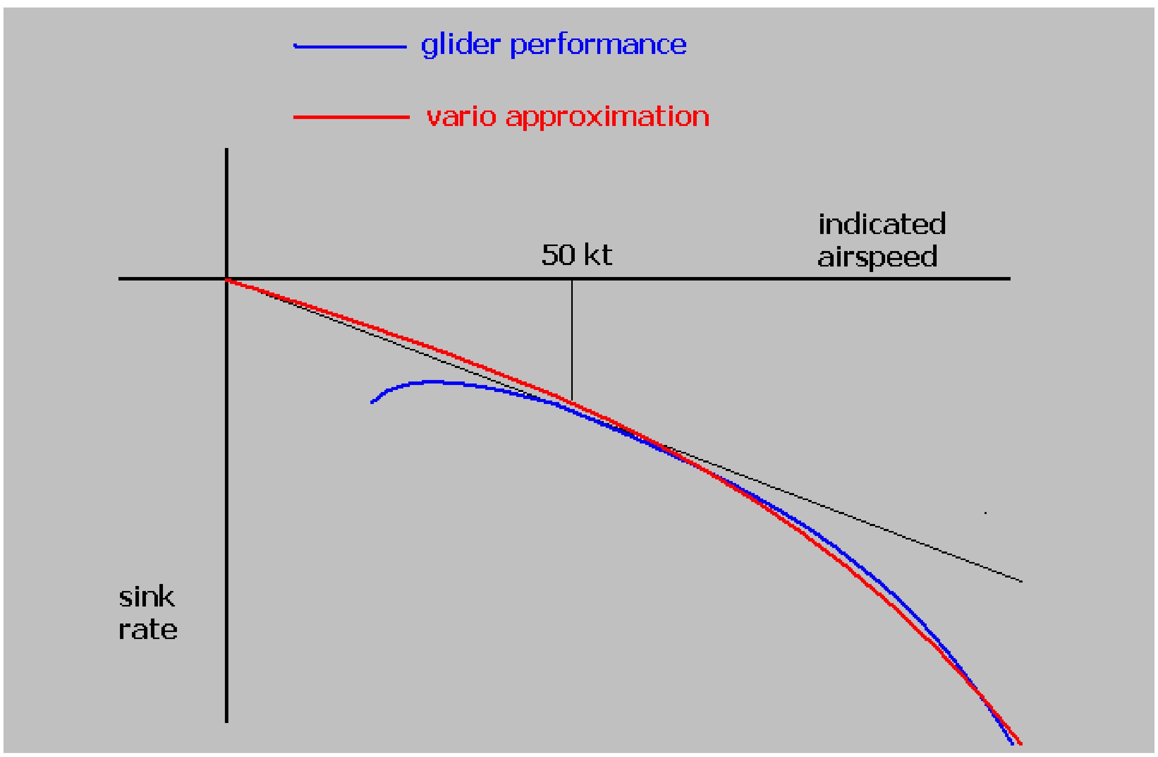
$$\text{Drag} = \frac{D}{L} \times \text{Lift} = \frac{\text{Lift}}{L/D} = \frac{\text{Weight}}{L/D} = \frac{800}{40}\ \text{lb} = 20\ \text{lb}$$

That’s right, the total drag of a typical 15-meter ship at best L/D is only about 20 pounds! You could sit in the back seat of the towplane and hold the tow rope in one hand...(not counting, of course, when the slack comes out in rough air.)

Induced drag, under these conditions, would be half of this, just 10 lb. Profile drag--primarily skin friction--would be the same: 10 lb.

But consider flight at 85 KIAS, a typical "dry" interthermal cruising speed. Under these conditions, profile drag (proportional to the square of the indicated airspeed) would have risen to 29 pounds, while induced drag (inversely proportional to the square of the indicated airspeed) would have decreased to about three and a half pounds. (And the L/D would now be about 25:1.)

We can see that, at high speeds, reducing profile drag is the name of the game; further, we can see that at high speed, induced drag isn't a major consideration. This means that we can neglect induced drag at high speeds and approximate the glider's performance curve with a simple parabolic model. As it happens, a quadratic approximation is relatively easy to provide electronically, and this is exactly what a speed-to-fly vario does internally:



Obviously, speed-to-fly vario guidance is really only helpful at speeds higher than that for best L/D. At lower speeds the quadratic approximation is so inaccurate as to be useless to a pilot.

A little historical digression

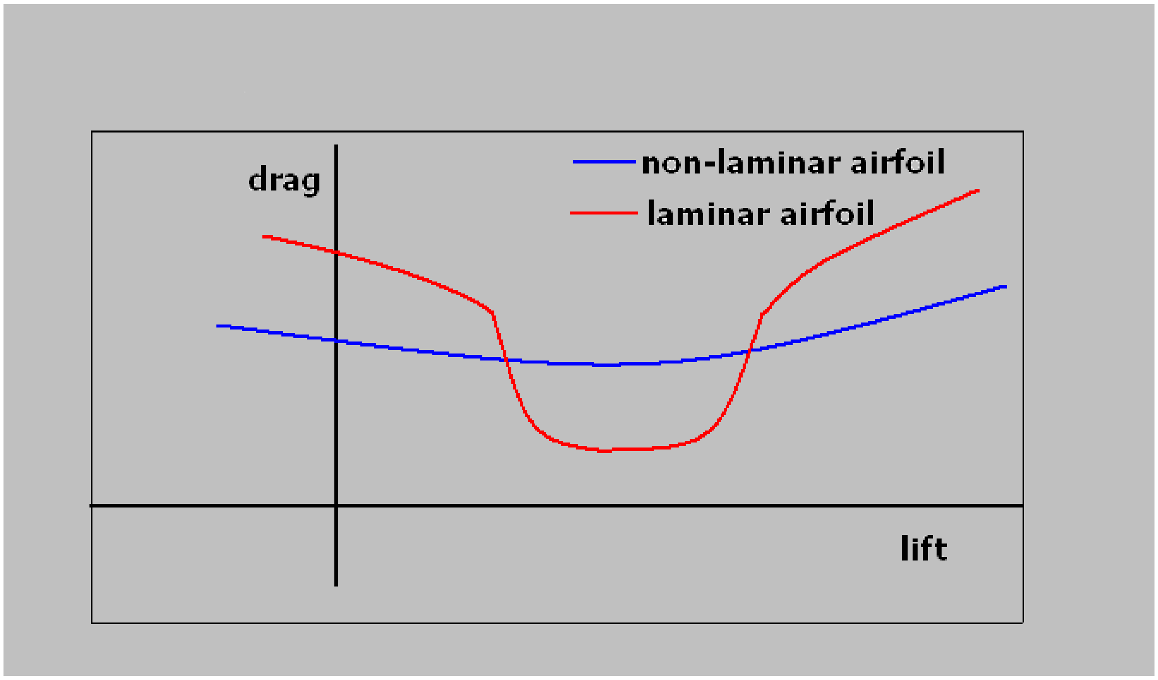
Since skin friction is the dominant source of drag at high speeds, a lot of attention has been devoted in recent decades to reducing it to the absolute minimum. This wasn't always the case; at the dawn of the sport of soaring, ridge soaring was the only game in town, and glider designers vied to create sailplanes with the lowest possible sinking speed—and since there was nowhere to glide to, maximizing L/D wasn't important. Soon after thermals were discovered, glider designers did their best to provide sailplanes able to maneuver within the tiny thermals found at low altitudes. This led to sailplanes with reasonable L/D's but low wing loadings; interthermal speeds were low, but contests centered on flying what we now call "free distance" flights, generally downwind. These were effectively duration tasks, as pilots simply tried to remain aloft long enough to float downwind further than their competitors. As the distances involved became significant, there was increasing pressure to fly closed courses so as to return to the starting point by the end of the day; this trend culminated in the modern high-wing-loading, dolphin-flying glass sailplane of today. And with this emphasis on high-speed cruising came additional emphasis on reducing skin friction, as most other sources of profile drag (nose skids, total energy venturis, lengthy tailskids, fixed landing gears, exposed control cables and bellcranks, etc) had already been pretty much eliminated.

One way to minimize skin friction is to minimize skin area; this is the reason modern fuselages dramatically contract immediately aft of the cockpit to form the familiar tailboom. (This is also the reason fin and rudder areas are just barely adequate to handle adverse aileron yaw.) Another approach is to minimize the amount of drag produced by each square inch of skin area...

In the 1940s aeronautical research turned to the problem of designing airfoils so as to encourage as much laminar flow as possible. Airfoil design is, conceptually, a two-step process: you first design a "thickness distribution"—a symmetrical airfoil-like shape with whatever pressure distribution you choose—and then you give it camber by bending it around a "mean line"—a sort of curved center line that connects leading edge with trailing edge and provides the chordwise distribution of lift you wish. Experimenters discovered that so long as the airflow was accelerating as it passed over (or under) the airfoil, it was easy to maintain low-drag laminar flow, but that as soon as the airflow began to slow down the flow transitioned to a turbulent boundary layer and skin friction increased. Not too surprisingly, the way to keep the airflow accelerating was to arrange to position as far aft as practical the point at which the airfoil reached its maximum thickness. This worked well for a symmetrical airfoil at zero angle of attack, but...

...for airfoils hard at work creating lift, the chordwise point at which the airflow reached its peak velocity moves forward as the angle of attack is increased. For the older, pre-laminar-flow airfoils, this was a gradual process; for a laminar flow airfoil, however, the process is fairly abrupt: at some particular angle of attack,

the transition point suddenly jumps forward. Worse yet, once this happens, the drag jumps up to a level significantly higher than would be observed with a non-laminar airfoil! Here's a typical comparison:



Notice that there is a range of angles of attack within which the laminar wing offers us much lower drag; this is the famous "drag bucket." Notice, too, that once we leave this range and fly at either very high or very low angles of attack, we pay a large drag penalty: our vaunted "low-drag" airfoils are no longer working for us!

What does this mean? Well, for one thing, it means that the old advice—to fly as slowly as possible when circling in thermals—no longer makes much sense. In fact, when flying a sailplane with a laminar-flow wing,

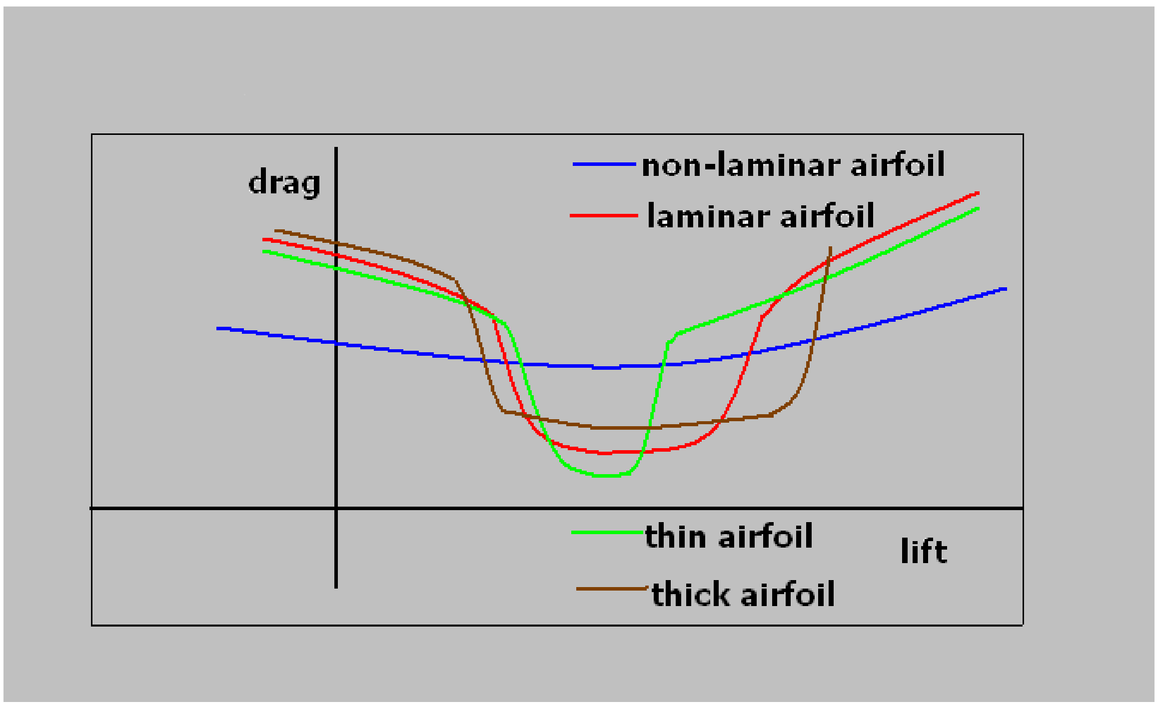
If you fly too slowly in thermals, you might as well thermal with your spoilers cracked partially open!

But how slowly is "too slowly?" What speed should you use? In the typical modren glass, laminar-flow sailplane, a good starting point would be to thermal at the same IAS at which wings-level L/D is achieved; the optimum speed to use in thermals will probably be within a couple of knots of this speed. Let's highlight this point:

Thermal at best L/D speed.

(Since the earliest applications for laminar airfoils were piston-powered fighters of the 1940s—such as the P-51 Mustang—this wasn't much of a consideration: contemporary sources estimated that escort fighters spent at least 95% of their time aloft in straight and level flight. For us, however, who typically spend at least 30% of our cross-country flights circling in thermals, this drag penalty is significant. One of F.X. Wortmann's earliest contributions to airfoil design was the careful tailoring of the aft portion of his thickness distributions so as to somewhat reduce the drag penalty incurred in thermals.)

Let's take another look at the laminar drag bucket:



Here we've drawn in a couple of other laminar airfoils—one thinner, one thicker than in the original drawing. Notice the effect of thickness: the thinner the wing, the lower the drag at the bottom of the drag bucket; however, the thinner the wing, the narrower the drag bucket becomes. This suggests two contrasting approaches to the problem of designing a low-drag wing: the designer can either choose a thick airfoil, and reap the benefits of laminar flow over a broad speed range—or he can choose a thin airfoil, and somehow ***move*** the drag bucket to whetever the pilot needs it at any given moment.

But how can he do ***that***?

Recall that the design of an airfol involved two steps: first you choose a thickness distribution, then you choose a mean line with which to camber it. As it turns out,

while the width of the drag bucket depends largely on the thickness of the airfoil, the position of the drag bucket depends on the amount of camber the airfoil has: more camber means the drag bucket will occur at a higher angle of attack. But how can the pilot vary his camber in flight? That's easy—that's exactly what flaps do!

So, the typical 15-meter racer has a thin, flapped wing, and the typical Standard Class ship has (obviously) no flaps--but substitutes a thicker wing. Two choices, each accomplishing just about the same thing.

Turning Performance

Most of the time we're turning a sailplane we are doing so because we're trying to stay within a small region of rising air—typically, a thermal. Because we're not really going anywhere, the concept of L/D in a turn is pretty meaningless. What we're really after, instead, is the 'best' combination of low sink rate and small turn radius. We'll consider each of these factors separately, beginning with turn radius.

After converting units, etc, we can calculate turn radius as

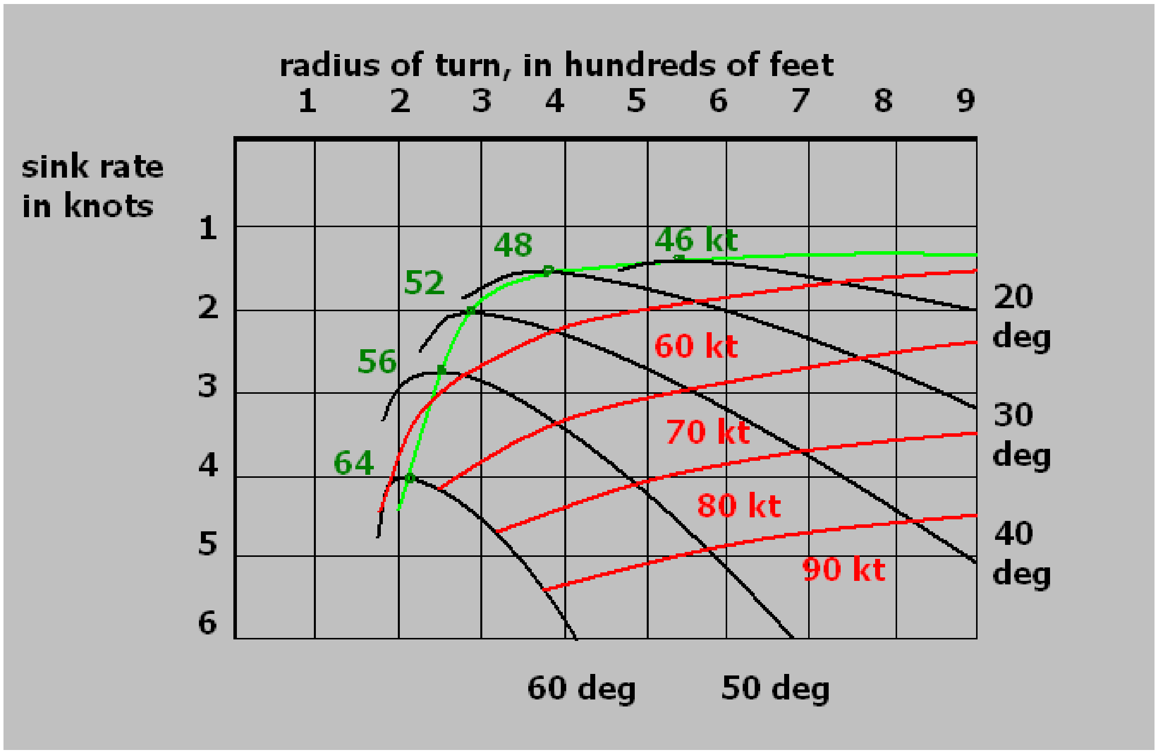
$$\mathbf{r = \frac{0.0886V^2}{\tan \theta}}$$

where V = true air speed in kts and θ = bank angle. Our ficticious glider, then, circling at 45 degrees of bank and at best L/D speed of 50 kts, would have a turn radius of 222 feet—<u>at sea level</u>.

At a density altitude of 10,000 feet, this turn radius would increase to 320 feet, and working the rocks at the top of the White Mountains, with a summertime density altitude of perhaps 17,500 feet, it would have a turn radius of 405 feet—nearly double the sea-level value! Until you get used to judging this effect, it pays to be conservative and to play it safe.

Now to consider sink rate. At any given IAS, profile drag—skin friction and all the like—is constant; however, in a turn your increased load factor requires a substantial increase in the amount of lift that must be generated, and this leads to a dramatic increase in induced drag. In fact, at a given IAS induced drag will vary in proportion to the square of your load factor—so that in a 60-degree bank it will be **four times** the wings-level value! (The drag of our ficticious 15-meter sailplane will have risen from one-fortieth of the weight to one-sixteenth—this would correspond to a glide ratio about two-thirds as good as that of a 1-26.) This is the reason your sink rate is so much higher in a steep turn as compared to wings-level flight.

Considering turn radius and sink rate together, we'd see something like this:



In this figure, the black curves are lines of constant bank angles, the red curves are lines of constant airspeed—and the green line is the envelope of minimum sink rates for each bank angle.

Notice that the 'best' compromise between small circle radius and low sink rate lies somewhere between 40 and 50 degrees of bank—and that the minimum sink rate for banks in this range occurs right around the speed for best wings-level lift-to-drag ratio. (These figures, as well as this diagram, apply broadly to most modern 15-meter and Standard Class sailplanes.)

Now, in a temperate region with weak, large-diameter thermals, it may often turn out that fairly shallow bank angles result in the best climb rates. However, here in the Great Basin, bank angles between 40 and 50 degrees generally result in the best climb rates. It is convenient to use 45 degrees because every cockpit provides a ready visual reference for this bank angle... Most of the round instruments in a sailplane cockpit are fastened to the instrument panel by four screws arranged in a square pattern; aligning any two diagonally-opposite screws so that a line drawn between them parallels the natural horizon will result in a bank angle of exactly 45 degrees—and if you can see it, you can fly it.

Approach Performance

OSTIV or, more recently, JAR certification standards generally require that the descent gradient at approach speed must be steeper than 7:1, and in fact most sailplanes are capable of flying a stabilized approach at a 6:1 glide slope. The recommended approach speed is generally the same IAS for best L/D, plus the usual additions for steady winds or gusts. Our ficticious 800-lb sailplane would therefore have to generate a total drag force of

$$\frac{\mathbf{800\ lb}}{\mathbf{6}} = \mathbf{133\ lb}$$

Since this must be the case while flying at an IAS very close to our 50-kt best glide speed, we can assume that the basic aircraft generates about the same drag as before at this speed—that is, 20 lb. The remaining 113 pounds of drag must therefore be largely produced by the drag devices; since on the typical modern sailplane these would take the form of a pair of dive brakes on the wing upper surface only, each of these must therefore create more than 50 pounds of drag each. At 100 knots, each of these must generate four times as much drag—or more than 200 pounds each! The wing structure to which they are attached must be capable of withstanding these large forces. It is easy to see that the design of drag devices really can't be at all an afterthought; rather, they represent a major part of the engineering effort involved. By the same token, your dive brakes are worth careful checking during every preflight inspection! It doesn't pay to neglect them. Please don't!

Aerotowing Performance

We generally aerotow at a speed just a bit higher than that for best L/D, so as a first assumption the glider's total drag would be just a bit greater than 20 pounds. By comparison, let's assume a towplane weighs 2400 pounds gross and has a power-off glide ratio of 8:1 with the propeller removed. In this case, the towplane's total drag would be about 300 pounds—vastly greater than the sailplane's drag. Clearly, the sailplane's drag simply isn't significant. As a matter of fact, since

power = drag x speed

The power required to support our ficticious sailplane in flight at 50 knots TAS would be about 18.4 horsepower—less than 10% of the typical towplane engine's 235-hp output.

What IS significant is the weight of the sailplane, which must be lifted by the towplane's engine. To lift our 800-lb glider at 500 ft/min would require

$$\frac{\textbf{800 lb x 500 ft/min}}{\textbf{5500 ft-lb/min/hp}} = \textbf{72.7 hp}$$

which is about one-third of the towplane engine's output. So the weight, NOT the drag, of the sailplane is the principal source for the poor climb rate of the towplane when it is towing a glider. Incidentally, these figures would be even more impressive at high density altitude, because while the drag and weight of the sailplane would be unchanged, the true air speed would increase—and the power required to overcome the drag varies directly with the TAS. As for the climb rate, the power available from the engine decreases with increasing density altitude. This results in a reduced climb rate, which, when combined with the increased true air speed, leads to a dramatically reduced climb gradient.

Special Performance Factors

Water Ballast

At any given angle of attack, the effect of increased gross weight is to increase the indicated airspeed as well as the rate of sink—in such a way that the L/D *at that angle of attack* remains constant. This effectively "stretches out" the performance polar so that high glide ratios are obtained at high speeds, while glide performance at low speeds is reduced. (In this context, the dividing point between "high" and "low" speed occurs at the IAS for best L/D.) This much is fairly well known among glider pilots, even though it is fairly rare for a pilot to actually use water ballast.

What is less well known is that the effect of water ballast can be obtained simply by flying at hgh density altitudes—which, of course, is pretty commonly done here in the Great Basin. For a concrete example, the same effect can be experienced by ballasting up to 150% of the sailplane's 'dry' gross weight, or by flying at a density altitude of just 11,000 feet msl. The reason is that either ballasting the glider or flying at high altitude increases the ratio between the density of the aircraft and that of the air surrounding it. The only difference between the two lies in the distribution of the extra mass, so that for example the sailplane's rolling performance is not as affected by flight at high altitude as by flight with ballast carried in the wings.

Winglets

The intended effect of winglets, when they first appeared, was to decrease induced drag by simulating a higher aspect ratio. They do this by slightly

increasing the distance between the wingtip vortices of either wingtip. Properly designed, they do this without the increased spanwise bending moment—the tendency of the lift forces to bend the wingtips up when the wing is supporting the sailplane--that would otherwise arise with wingtip extensions. In the 15-Meter, 18-Meter and Standard classes, of course, they also provide a way of coping with the span limitations imposed by the respective class rules.

Later winglet designs also improved aileron control response, and indeed in most modern sailplanes equipped with winglets this is the major benefit. As such, we should consider winglets not as performance enhancements, but rather as handling improvements—in much the same way that, for example, flapped sailplanes (especially when operated at high density altitudes) benefit perhaps not so much from improved performance, but from improved takeoff and landing roll performance.